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6. AUTHOR(S)
Earl H. Dowell

Robert L. Clark, Jr.

Lawrence N. Virgin

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Mech. Eng. and Materials Sciences
Pratt School of Engineering
P.O. Box 90300
Durham, NC 27708

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14. ABSTRACT

Experimental and theoretical studies of the nonlinear dynamics and control of aeroelastic systems including airfoils and wings have been conducted. Nonlinear geometric stiffness and freeplay have been considered specifically and good theoretical / experimental correlation obtained. Active control systems have been designed, built and tested to increase flutter speed and reduce limit cycle oscillations (LCO). Our most recent work includes theoretical studies of aerodynamic nonlinearities in the transonic range and their effect on flutter and LCO.

15. SUBJECT TERMS
Aeroelasticity, Nonlinear Dynamics, Control, Flutter, Limit Cycle Oscillations (LCO)

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FINAL REPORT TO THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
"DYNAMICS AND CONTROL OF NONLINEAR FLUID-STRUCTURE INTERACTION"

AFOSR GRANT NUMBER F49620-00-1-0030

Earl H. Dowell, PI
Department of Mechanical Engineering and Materials Science
School of Engineering, Duke University, Durham, N.C.

Robert L. Clark, Jr. CO-PI and Lawrence N. Virgin, CO-PI
Department of Mechanical Engineering and Materials Science
School of Engineering, Duke University, N.C.

July 2003

OBJECTIVE

To develop a more fundamental understanding of the causes and control of limit cycle oscillations and other dynamic phenomena arising from nonlinear effects in aeroelastic systems. Combined experimental-theoretical studies are being pursued to assess, validate and improve our physical understanding. Mathematical models for design and analysis to enable flight of aircraft safely and reliably beyond the conventional and traditional flutter boundary are being developed.

RELATIONSHIP AND IMPORTANCE TO AFOSR

Some current Air Force flight vehicles are known to undergo limit cycle oscillations (LCO) due to as yet undetermined nonlinearities. If the source of these nonlinearities can be identified and accurately modeled mathematically, then such effects can be predicted and exploited in the design phase of new aircraft and/or modified existing aircraft. More specifically we know empirically through flight experience that some LCO can be tolerated without compromising mission performance while other LCO cannot. By developing an improved understanding and predictive capability for LCO, then it may be possible to design aircraft to operate safely and reliably beyond the conventional linear flutter boundary. This will lead to enhanced mission capability as well as increased flight safety.

BASIC RESEARCH ISSUES

The likely aerodynamic and structural nonlinear mechanisms are several. For the flow field, viscous effects leading to separation and/or compressible effects leading to shock waves may create a nonlinear relationship between the structural motion and the fluid response, e.g. the pressure acting on a wing or panel. Structural nonlinearities of interest include freeplay in the attachments between airframe elements, e.g. the control surface and the wing. Freeplay leads to a bi-linear stiffness, i.e. a very low stiffness for small amplitude motions and a much larger, nominal stiffness (the ideal stiffness without freeplay) at larger amplitudes. Also the wing itself may have geometric (stiffness) nonlinearities arising from coupling between in-plane and out-of-plane structural motion. This coupling creates a nonlinear tension stiffening induced by

in-plane stretching of the wing as a consequence of wing bending. Finally nonlinear structural damping arising from dry friction forces may play a role in LCO.

Until recently none of these nonlinear mechanisms has been subject to a systematic theoretical/experimental investigation to assess the importance of each of the several nonlinearities and our ability to model them accurately. Such a study is being conducted with the support of the present grant.

APPROACH AND STATUS OF EFFORT

The focus of the present grant effort was initially on structural nonlinearities as they affect the total aeroelastic system behavior, rather than on the study of aerodynamic nonlinearities. This was for two reasons. One is that aerodynamic nonlinearities are being addressed in a companion grant and the other is that the structure is a more likely candidate for making design choices to create desirable nonlinear effects and to avoid undesirable ones.

In the first phase of our work we examined a prototypical model of an airfoil with a control surface attached. The attachment has a nominal linear spring stiffness behavior, but also incorporates a freeplay nonlinearity. An experimental model was built and tested in the Duke wind tunnel and the experimental results for LCO were correlated with those of a mathematical model that included the structural nonlinearity and a linear aerodynamic model. The correlation was very good for LCO response including amplitude and frequency of the motion. A transition from one type of LCO to another was predicted theoretically and observed experimentally. [1-4] More recent work has shown the effectiveness of various control approaches in modifying or eliminating LCO and also investigated more deeply the nature of the several types of LCO that may occur and the transition from one to another.
[5, 6]

In Figure 1 a photograph of an airfoil wind tunnel model with freeplay is shown. Earlier work has shown good correlation of theory and experiments (conducted at low Mach number) for LCO response as a function of flow velocity [1-4]. More recent work has extended the theoretical LCO calculation to transonic flow using a aerodynamic Reduced Order Modeling capability developed under a companion grant [7].

Another prototypical model used in the grant work has been a low aspect ratio delta wing that has been constructed for experimental study. See Fig. 2. This wing model is of constant thickness and has the structural behavior of a plate (as distinct from a beam/rod). The structural nonlinearity is the tension induced by bending discussed above. Again theoretical/ experimental correlation has been good. More recent results are for the delta wing placed at a steady angle of attack. The steady angle of attack gives rise to a steady loading on the wing that deforms the wing statically, thereby changing the effective linear stiffness as well as the nonlinear stiffness of the wing structure. Two significant theoretical predictions have been made. On the one hand, the flow velocity for the onset of the LCO (i.e. the flutter speed) is reduced by increasing the angle of attack, but on the other, the amplitude of the LCO is also reduced. So there is both a positive and a negative impact of a non-zero angle of attack. Also recent tests have examined the effects of various control methods and investigate the nature of the LCO in more depth, for

example changes of flutter mode shape with airspeed. [8-11]. Again the focus is on theoretical/experimental correlation and fundamental physical understanding leading to reliable modeling for analysis and design.

As another phase of our work we have considered the effects of gust loading on both the airfoil and wing models. For linear systems the effects of flutter and gust response may be considered separately, but for nonlinear systems there is a nonlinear interaction between gust excitation and LCO and thus simple linear superposition no longer applies. [12, 15] Again good correlation between theory and experiment has been obtained.

Other recent work has focused on system identification of linear and nonlinear aeroelastic systems [16, 17, 18] and on active control [19, 20] of such systems. System identification of unsteady aerodynamic models has been successful [16] and promising results have been obtained for a nonlinear aeroelastic system with freeplay [17, 18].

Also a new airfoil experimental model has been used to investigate more deeply the effects of control system dynamics and the transition between various LCO. A basic question is how do the control dynamics interact with those of the aerodynamic flow and the structure and does the presence of a control system add to the complexity of the aerodynamic and structural models needed for reliable predictions and design? Current work is underway to address these issues. Also, certain nonlinearities in the control system will be modeled in future work as well as structural nonlinearities. [19, 20].

A new delta wing model has also been used as a prototype to study the added complexities of control system dynamics, as is being done for the airfoil. The first set of wind tunnel tests with this model has been completed to identify optimum locations for piezoelectric sensors and actuators. [21]

It is noted that a key enabling methodology in the studies reported here has been the use of reduced order aerodynamic models that have been and are being pursued under a separate grant. This has allowed the recent extension of the mathematical model for the airfoil with control surface freeplay to the transonic flow regime. A similar extension is planned for the delta wing model.

Much of our work under this grant has been summarized in the 2002 AIAA Theodore Von Karman Lecture [22]. Future work will include a theoretical/experimental study of nonlinear structural damping effects and also nonlinear aerodynamic effects.

SIGNIFICANT PAST RESULTS AND ACCOMPLISHMENTS

A deeper understanding of two prototypical structural nonlinearities due to free-play and large strain displacement (nonlinear stiffness) on LCO has been obtained. This suggests that reliable and practical analysis and design methods can be developed, not only for the relatively simple models investigated here which contain the fundamental physics for such nonlinearities, but also for the more complex structures encountered in flight vehicles.

Specifically, it has been shown experimentally and theoretically that aeroelastic systems may be operated safely beyond the onset of LCO and their responses predicted accurately and reliably for the nonlinearities investigated here. Our most recent work includes the nonlinear interaction of LCO and response to gust excitation as well as active control of these nonlinear aeroelastic systems.

CURRENT AND FUTURE DIRECTIONS

Current and future work is focused on parametric studies of LCO induced by nonlinear transonic aerodynamics including correlation with wind tunnel test date for the BACT wing [23] and the improved correlation between theory and experiment obtained by using a higher order plate theory beyond the classical Von Karman plate theory [24].

From [23], a comparison between theory and experiment for the flutter boundary is shown in Figure 3a and a family of LCO amplitude vs. reduced velocity plots for several different Mach numbers is shown in Figure 3b. Note the LCO due to nonlinear aerodynamic effects may be either stable or unstable, i.e. the LCO response plots may bend to the right or left, as the Mach number is varied.

In Figure 4, results are shown for the delta wing LCO amplitude vs. flow velocity from the Von Karman plate theory, a higher order plate theory and experiment. Note the higher order theory gives better agreement with experiment.

ACKNOWLEDGMENT/DISCLAIMER

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PUBLICATIONS

1. Conner, M.C., Virgin, L.N. and Dowell, E.H., "Accurate Numerical Integration of State-Space Models for Aeroelastic Systems with Freeplay", AIAA Journal, Vol. 34, 1996, pp. 2202-2204.

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3. Tang, D.M., Dowell, E.H. and Virgin, L.N., "Limit Cycle Behavior of an Airfoil with a Control Surface", Journal of Fluids and Structures, Vol. 12, 1998, pp. 839-858.

4. Tang, D.M., Conner, M.C. and Dowell, E.H., "Reduced Order Aerodynamic Model and Its Application to a Nonlinear Aeroelastic System", Journal of Aircraft, Vol. 35, No. 2, 1998, pages 332-338.

5. Vipperman, J.S., Clark, R.L., Conner, M.D. and Dowell, E.H., "Experimental Active Control of a Typical Section Using a Trailing-Edge Flap", Journal of Aircraft, Vol. 35, No. 2, 1998, pp. 224-229.

6. Clark, R.L., Dowell, E.H. and Frampton, K.D., "Control of a Three Degree-of-Freedom Airfoil with Limit Cycle Behavior", AIAA Journal, submitted for publication.

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8. Tang, D.M., Dowell, E.H., and Hall, K.C., "Limit Cycle Oscillations of a Cantilevered Wing in Low Subsonic Flow", AIAA Journal, Vol. 37, No. 3, 1999, pp. 364-371.

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Airfoil Typical Section with Control Surface Freeplay

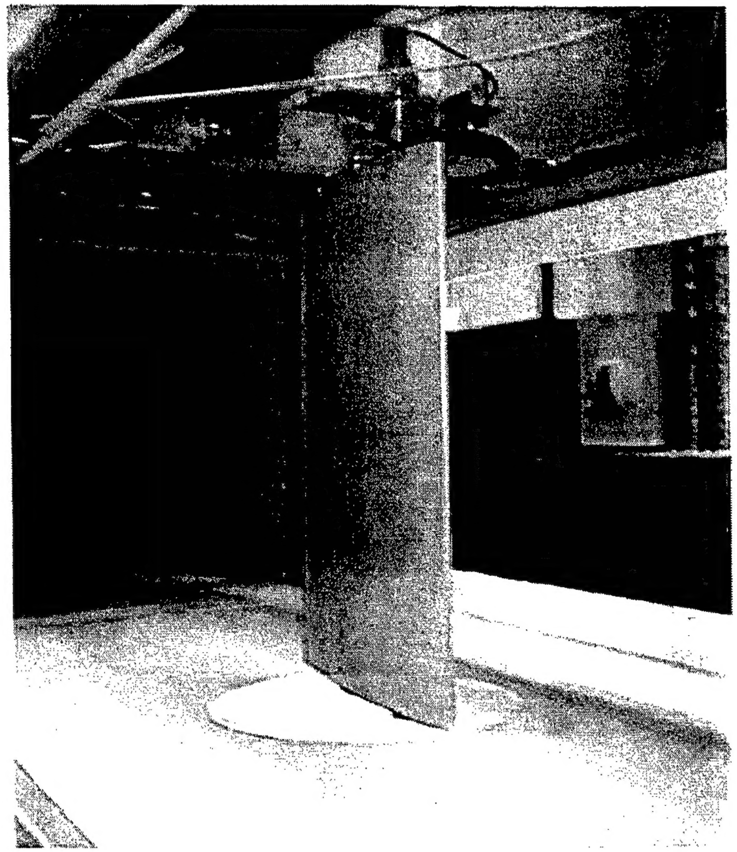

FIGURE 1

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Delta Wing with Stiffness Nonlinearity

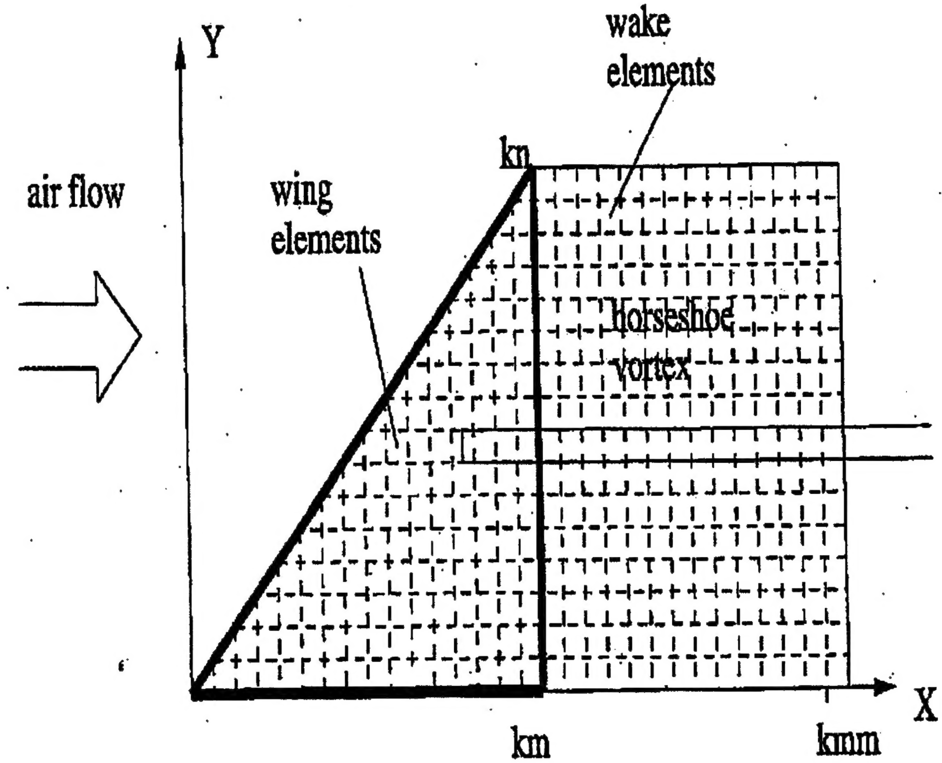

FIGURE 2a

Delta Wing Wind Tunnel Model

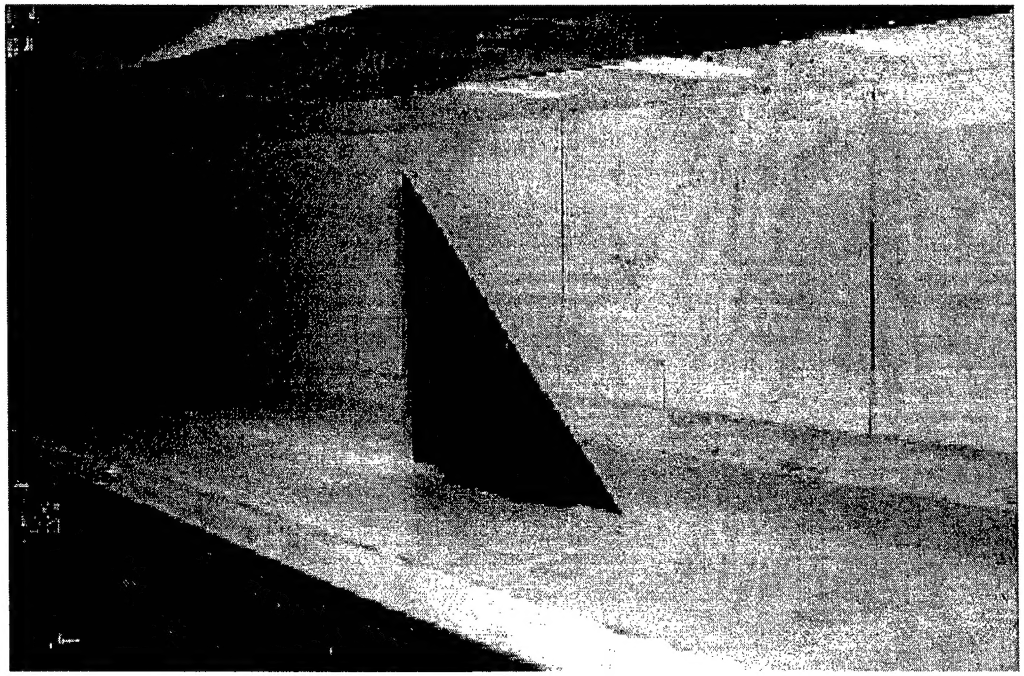

FIGURE 2b

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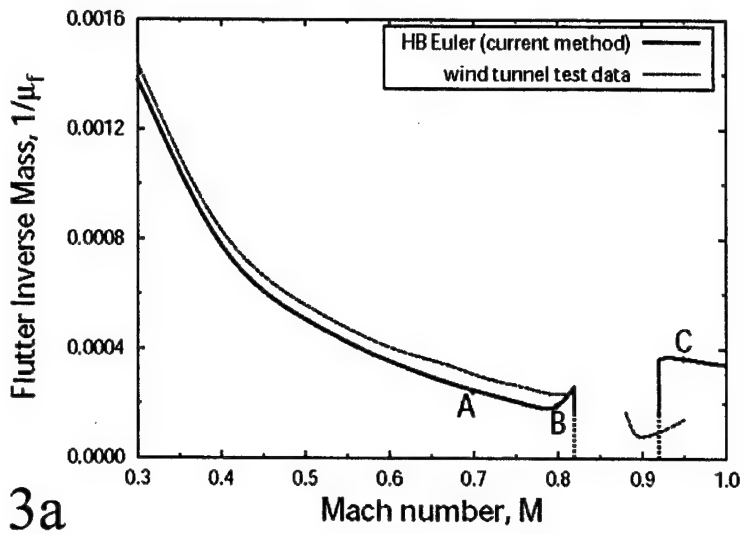
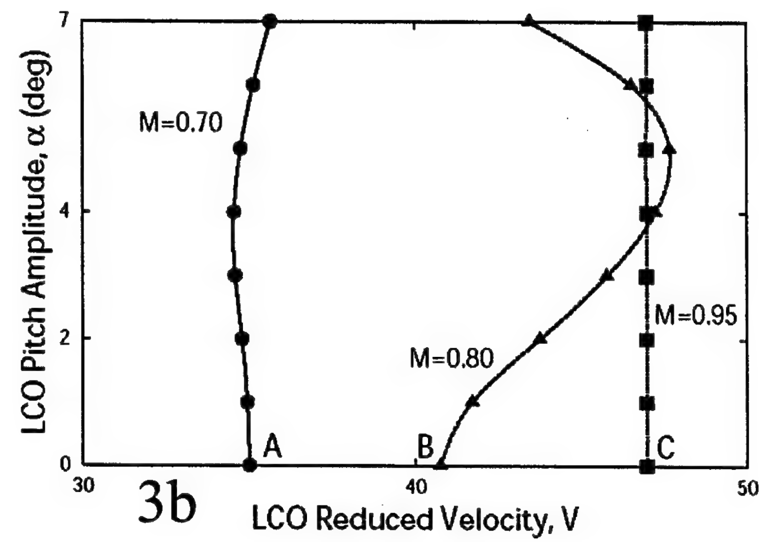
Figure 3a: Flutter Boundary for BACT Wing: Theoretical/Experimental Correlation for Mass Ratio vs. Mach Number



3a



3b

Figure 3b: LCO Amplitude vs. Reduced Flow Velocity for Several Mach Numbers of BACT Wing

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Chart #3 (cont'd 5)

FIGURE 3a & 3b

Improved Theoretical/Experimental Correlation for Delta Wing Using a Higher Order Plate Theory

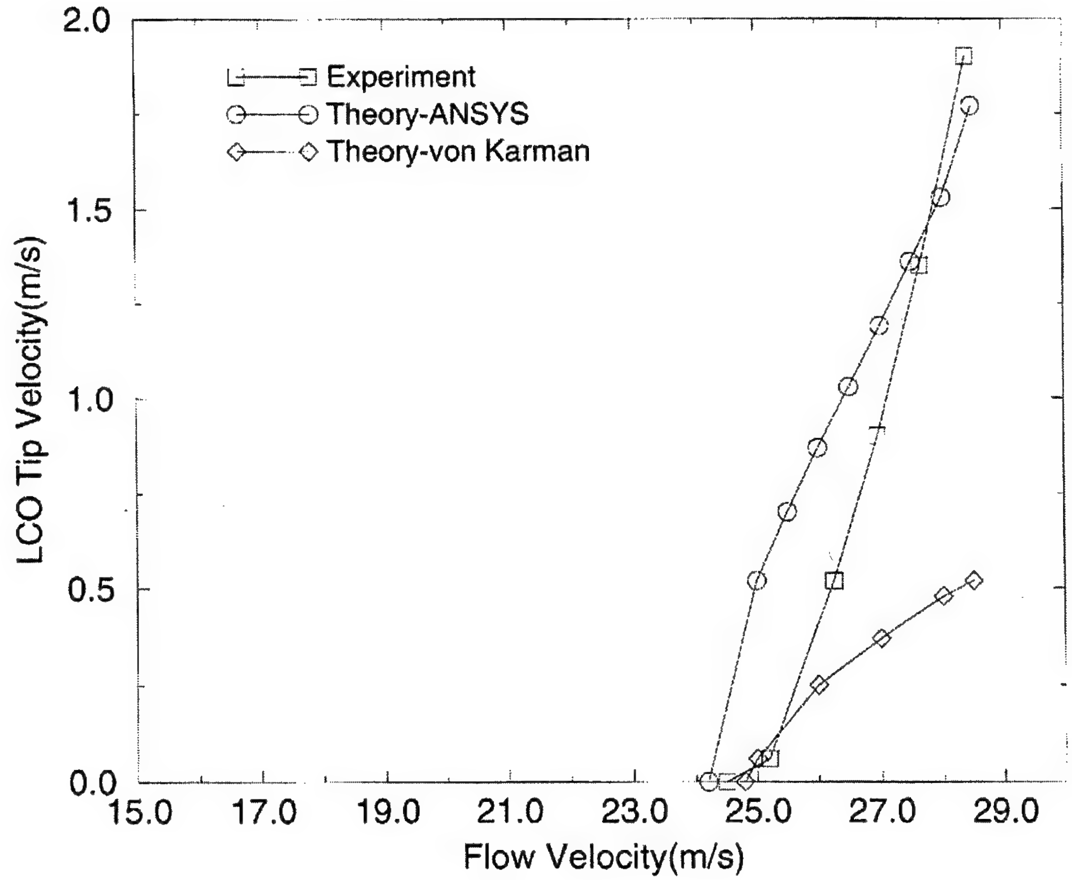

Chart #3 (cont'd 6

FIGURE 4

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Name (Last, First, MI): **Dowell, Earl H.**

Institution: **Duke University**

Contract/Grant No.: **F496F20-00-1-0030**

NUMBER OF GRANT/CONTRACT CO-INVESTIGATORS

Faculty: **2** Post-doctorates: **1** Graduate Students: **1** Other:

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NOTE: List names in the following format: Last Name, First Name, MI
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HONORS AND AWARDS **(Earl H. Dowell, Duke University, F496F20-00-1-0030)**

2002	AIAA Theodore Von Karman Lectureship
1994	Distinguished Service Award, American Academy of Mechanics
1993	Fellow, the American Society of Mechanical Engineers
1993	Elected Member, National Academy of Engineering. Past Chair, Honors and Awards Committee
1990	President, American Academy of Mechanics
	University of Illinois College of Engineering Alumni Honor Award for Distinguished Service in Engineering for "continuous contributions to his profession through diligent research and dedication as an outstanding scholar and educator"
1989	Distinguished Annual Lecturer, AIAA Structures, Structural Dynamics and Materials Meeting
1984	Fellow, American Institute of Aeronautics and Astronautics
1983	Fellow, American Academy of Mechanics
1980	AIAA Structures, Structural Dynamics, and Materials Award for "unceasing outstanding scientific contributions in aeroelasticity and structural dynamics which provide constant insights into the behavior of complex structural systems - a 'universal man' in his field and an extraordinarily skillful teacher."
1977	Who's Who in America
1975	Distinguished Alumnus Award, Aeronautical and Astronautical Engineering, University of Illinois